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COMPUTER SYSTEMS LABORATORY

DEPARTMENTS OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE
STANFORD UNIVERSITY · STANFORD, CA 94305

PERFORMANCE EVALUATION OF MULTIHOP PACKET RADIO SYSTEMS

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FINAL REPORT

Period 8/6/79-11/5/82

Contract #DAAG 29-79-C-0138

Pricipal Investigator: Fouad A. Tobagi

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This is the final report for the research carried out at the Computer Systems Laboratory under the ARO contract number DAAG 27-79-C-0138 during the period from August 6, 1979 to November 5, 1982. The research effort related to packet radio systems and their evaluation. Throughout the contract period, the effort mainly focused on one important aspect underlying these networks, namely the channel access problem. The following areas were investigated

20. (continued)

resulting in significant accomplishments reported upon in the open literature:

1) Distribution of packet delay and interdeparture times in slotted ALOHA and Carrier Sense Multiple Access.

2) P-CSMA: Carrier Sense Multiple Access with message-based priority functions.

3) On voice communication and CSMA networks.

4) Busy Tone Multiple Access in multihop packet radio networks.

Performance Evaluation of Multihop Packet Radio Systems

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Fouad A. Tobagi

December 4, 1982

U. S. ARMY RESEARCH OFFICE

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1. Introduction

This is the final report for the research carried out at the Computer Systems Laboratory under the ARO contract number DAAG 29-79-C-0138 during the period from August 6, 1979 to November 5, 1982. The research effort related to packet radio systems and their evaluation.

A packet radio network is a collection of geographically distributed, possibly mobile packet radio units (PRU's), communicating with each other over a shared broadcast radio channel. Data originates at some PRU's (referred to as sources), is destined for other PRU's (referred to as destinations) and is transmitted in packetized form. Since a radio transmitter may be unable to reach its destination due to power limitation and because the topology may include obstacles that are opaque to radio signals, PRU's also act as repeaters which relay packets in a store-and-forward manner between sources and destinations. So a message transmitted by the source might travel over many hops before reaching the destination.

There are many variables that need to be considered in the design of packet radio systems. Some of these are determined by the general objectives of the system. For example, all devices employ omnidirectional antennas in order to facilitate communications among mobile users. Other design variables have to be optimally selected so as to achieve the most cost-effective design. Among the variables to be selected are: network topology, which consists of the number of devices and how they are configured; the modulation and data encoding schemes used on the radio channel; the channel access policy by which the radio devices access the shared radio channel; the routing and flow control protocols which determine the flow of internal traffic in the network; and finally the nodal design which includes the selection of the storage capacity at each node and the buffer management strategy in use.

Throughout the contract period, the effort mainly focused on one important aspect underlying these networks, namely the channel access problem. Many access schemes have been devised which allow a set of geographically distributed users to access a common channel. As discussed in [14] these schemes differ in several respects namely the *static or dynamic nature of the bandwidth allocation*, the centralized or distributed nature of the decision making process, and the degree of adaptivity to changes in user demands. Accordingly they are grouped into different classes out of which, given the mobile radio environment, the class of random access techniques offers the desired feature of simplicity in providing access to the channel in a distributed dynamic fashion. The simplest random access protocol is ALOHA [1, 14] which permits users to transmit any time they desire. Under this protocol, the overlap in time and space of several transmissions which may occur on the shared channel, may induce significant errors in some or all of these transmissions, thus resulting in low channel efficiency. Carrier sense multiple access (CSMA) attempts to alleviate this problem by requiring the transmitter to sense the state of the channel (busy or idle) prior to transmitting and to inhibit transmission if the channel is sensed busy [9].

2. Statement of the Problems Studied

The following areas were investigated resulting in significant accomplishments reported upon in the open literature:

1. Distribution of packet delay and interdeparture times in slotted ALOHA and Carrier Sense Multiple Access.
2. P-CSMA: Carrier Sense Multiple Access with message-based priority functions.
3. On voice communication and CSMA networks.
4. Busy Tone Multiple Access in multihop packet radio networks.

In the following sections, we discuss the work accomplished in each of the areas and their relevance to the DOD program.

3. Summary of the Most Important Results

A. Distribution of Packet Delay and Interdeparture Time in Slotted ALOHA and Carrier Sense Multiple Access

As mentioned above, slotted ALOHA and CSMA are random access methods for multiplexing a population of users communicating over a shared packet-switched channel [14]. In slotted ALOHA the time axis is divided into slots of duration equal to the transmission time of a single packet (assuming constant-length packets). Users transmit any time they desire, as long as they start transmission of their packet at the beginning of a slot. If a conflict occurs (owing to time-overlapping transmissions), conflicting users reschedule transmission of their packets to some random time in the future [2, 7, 12, 14]. CSMA is a highly efficient random access scheme for environments where the propagation delay is short compared to the transmission time of a packet on the channel. Briefly, CSMA reduces the level of interference (caused by overlapping packets) in the random multiaccess environment by allowing terminals to sense the carrier due to other users' transmissions; on the basis of this channel state information

(busy or idle) the terminal takes an action prescribed by the particular CSMA protocol in use. In particular, terminals never transmit when they sense that the channel is busy [9, 14].

The difficulty in analyzing multiaccess schemes such as slotted ALOHA and CSMA arises from the fact that the system's outcome is at all times dependent on the system's state and its evolution in time; for example, the time required to successfully transmit a packet is a function of the evolution of the number of contending users during the lifetime of the packet. To analyze the performance of sotted ALOHA and CSMA, Markov and semi-Markov models have been formulated for channels with *finite* populations of users, each user possessing a *single* packet buffer [8, 19, 21]. Average stationary performance has been derived in terms of average throughput and average packet delay. As the average performance may not be adequate when designing systems intended for real-time applications such as digitized speech, the analysis has to be extended so as to include delay distributions. Also, when analyzing multihop systems, it is important to be able to characterize the departure process from a collection of nodes, as this corresponds to the arrival process to other nodes. In this work we showed that using the same Markovian models, one can derive the actual distribution of packet delay, as well as the distribution of time separating consecutive successful transmissions (referred to as the interdeparture time). Moreover, it was shown that the analysis provides simple expressions for all moments of these distributions.

This work appeared first in *SEL Technical Reports #186* and *187* dated April 1, 1980 and culminated in a paper which appeared in the *Journal of the Association for Computing Machinery*, October 1982.

B. P-CSMA: Carrier Sense Multiple Access With Message-Based Priority Functions

In multiaccess/broadcast systems such as packet radio networks, all users share a common transmission medium over which they broadcast their packets. Each subscriber is connected to the common communication medium through an interface which

listens to all transmissions and absorbs packets addressed to it. New multiaccess schemes for packet broadcasting systems have been abundant in recent years [14]. However, little work has been done to incorporate message-based priority functions to these protocols. The need for priority functions in multiaccess environments is a clear matter: having multiplexed traffic from several users and different applications on the same bandwidth-limited channel, we require that a multiaccess scheme be responsive to the particular requirements of each user and each application. For a prioritized scheme to be acceptable, we require the following:

1. The performance of the scheme as seen by messages of a given priority class should be insensitive to the load exercised on the channel by lower priority classes. Increasing loads from lower classes should not degrade the performance of higher priority classes.

2. Several messages of the same priority class may be simultaneously present in the system. These should be able to contend on the communication bandwidth with equal right (fairness within each priority class).

3. The scheme must be robust in the sense that its proper operation and performance should be insensitive to errors in status information.

4. The overhead required to implement the priority scheme, and the volume of control information to be exchanged among the contending users, as required by the scheme, must be minimal.

To implement priority functions in these distributed environments, one needs to address three basic problems: (a) to identify the instants (which should be known to all users) at which to assess the highest current priority with ready messages, (b) to design a mechanism by shich to assess the highest nonempty priority class, and (c) to design a mechanism which assigns the channel to the various ready users within a class. The scheme proposed is the p-persistent prioritized CSMA (P-CSMA), which consists of resolving the first two problems by the means of reservation bursts and carrier sensing, and the third by using the p-persistent carrier sense multiple access [9, 14, 19, 21].

Two papers related to this topic have appeared in the literature. In the first by Franta and Bilodeau, the scheme consists of CSMA with different rescheduling delays assigned to the various devices; by staggering the delays, access right to the channel is prioritized across the devices and a gain in performance may be attained [5]. Unfrotunately, the scheme as described does not provide priority functions which are based on the messages to be transmitted. The second by Onoe et al. does provide message-based priority functions via the use of different preambles for the various priority classes of messages [6, 11]. However, in case of a collision between two equal priority messages, these are rescheduled into the future, resulting in an operatic which violates requirements (1) listed above.

P-CSMA is based on the principle that access right to the channel is ex sively granted to ready messages of the current highest priority level. It can .de preemptive or nonpreemptive, and is suitable to fully connected broadcast networks with or without the collision detection feature. We analyzed the p-persistent protocol of P-CSMA with two priority levels and derived the throughput-delay characteristics for each priority class. Finally, we discussed numerical results obtained from the analysis and from simulation, and thus evaluated the effect of priority functions and preemption on the throughput-delay characteristics for each class.

In the context of this study, the main effort supported by this contract was to design and write a simulation program for the evaluation of P-CSMA. The purpose of the simulation is twofold: (1) to cross-validate the results obtained from two models, and (2) to experiment with variations of the scheme, traffic patterns, and network loads which are no easily handled by analysis. For example, although the analysis of preemptive P-CSMA is feasible, the effect of preemption has been studied by simulation, as the number of different situations which arise in the preemptive case pertaining to the occurrence of various events is larger than in the nonpreemptive case, and thus renders the analysis a more tedious exercise. Futhermore, the analysis presents some limitations on the size of the system and on the load offered to the channel, for which the computations can be economically performed. The simulation is thus used to examine

larger systems and to verify that the behavior of P-CSMA is the same in both small and large systems. It is also important to note that the cross-validation of results from both models allows us to verify that (a) both the analytic and simulation models are correct; (b) the analysis is computationally feasible (and economically feasible for relatively small systems in that the accuracy of the computations is perfectly acceptable; and (c) the length of the simulation runs and the accuracy of the simulation results are acceptable without the need to povide confidence intervals. Finally, note that since the behavior of p-persistent CSMA has been extensively studied in the past and thus is fairly well understood [19, 21], we focused in this study on numerical results pertaining to the priority function and the effect of various system parameters on its performance.

SEL Technical Report #213, dated 1 June, 1981 reported the simulation work accomplished. Results of both analysis and simulation have been published in the *IEEE Transactions on Communications*, January 1982.

C. On Voice Communication and CSMA Networks

Commnications needs have primarily consisted of data communication applications such as computer-to-computer data traffic, terminal-to-computer data traffic, and the like. More recently, a new line of thought has been apparent. It is the desire to integrate voice communication on local data networks. The reason for this is threefold: (a) voice is a communication application just as computer data, facsimile, etc.; (b) recent advances in vocoder technology have shown that digitized speech constitutes a digital communication application which is within the capabilities of data networks; and (c) today's local network architectures, especially the broadcast type, offer very elegant solutions to the local communications problem, from both the point of view of *simplicity* in topology and device interconnection, and the point of view of *flexibility* in satisfying growth and variability in the environment.

While existing solutions are elegant, they are not without their limitations in performance. Some of these limitations arise as the characteristics of the environment and data traffic requirements being supported by these solutions deviate from those assumed

in the original design. Examples of such characteristics are: packet length distribution, packet generation pattern, channel data rate, delay requirements, geographical area to be spanned, etc.

In this effort we considered local networks of the broadcast bus type, exemplified by Ethernet [10], and investigated the performance of such systems when supporting voice communication. In particular we studied the effect on performance of various system parameters, such as channel bandwidth, vocoder rate, delay requirement, allowable packet loss rate, etc. For comparison purposes, we also considered an *ideal* conflict-free TDMA case which is undoubtedly the most suitable for voice traffic exhibiting a deterministic generation process, and thus provides the ultimate performance one can achieve.

The performance of a CSMA broadcast bus system is normally characterized by two main measures: channel capacity and the throughput-delay tradeoff. Channel capacity is defined as the maximum throughput that the network is able to support. The throughput-delay measure is the relationship which exists between the average packet delay and the channel throughput. It should be clear that, due to collisions and retransmissions, channel capacity is always below the available channel bandwidth, and that throughput and delay have to be traded off: the larger the throughput is, the larger is the average packet delay.

Both stochastic analysis and computer simulation have been previously used to evaluate the average stationary performance of CSMA and P-CSMA [9, 17, 19]. In that modeling effort it was assumed that for each user the packet intergeneration time is a random variable with a memoryless distribution. When dealing with voice applications, such an assumption is not adequate as the packet generation process is to a first approximation deterministic. Moreover, due to the real-time constraints encountered in voice communication, average performance is not sufficient, and one has to derive the distribution of delay or delay percentiles. This renders stochastic analysis rather difficult, and therefore we resort to simulation techniques for our study. The

version of the simulator used in this investigation is that corresponding to P-CSMA. This was done with the intent that if voice and data were to be integrated on the same network, then, due to the strict end-to-end delay requirement in voice applications, one suspects that the prioritized scheme would be more appropriate. Indeed, by giving priority to voice packets over data packets, the scheme will help guarantee to a certain extent the delay constraint for voice packets even in the presence of data traffic. In fact, analysis and simulation of P-CSMA with two classes of traffic has already provided indication to that effect [17]. Note, however, that in the present study we considered that there exists only one class of traffic, namely voice, and that it is given the highest priority. The only difference between P-CSMA and CSMA in this case is that with the former there is an additional overhead incurred in the implementation of the priority function which degrades the performance slightly as compared to CSMA.

When supporting voice communication, we define network performance as the maximum number of voice sources accommodated for a given maximum delay requirement and a tolerable packet loss rate. We studied the effect on this performance of various system parameters such as channel bandwidth, vocoder rate, delay requirement and packet loss rate. We compared these results to an ideal TDMA system which provides the ultimate best achievable performance. The results show that for a given delay constraint D_n and a given tolerable loss rate L, there is an optimum packet size B_v which provides the maximum number of voice sources. As long as the delay requirement D_n is not too severe ($\simeq$ 200 msec.) and the channel bandwidth W is not too large (1 MBPS), then the performance of P-CSMA is comparable to that of ideal TDMA. However, if either D_n is small ($\leq$ 20 msec.) or W is large ($\geq$ 10 MBPS), or both, then P-CSMA becomes inferior to the ideal case regardless of the vocoder rate. this is basically due to relatively small transmission time of a packet for which P-CSMA is known to have a poor performance. As a result, we note that, when the delay requirement is low, an increase in channel bandwidth with the expectation of increasing the maximum number of voice sources is rewarded by smaller than proportional improvement.

Detailed discussion of these issues appeared in *SEL Technical Report #213* and

in a conference paper presented at INFOCOM '82, April 1982.

D. Busy Tone Multiple Access in Multihop Packet Radio Networks

Analyses of random access schemes have previously focused mainly on single hop environments, assuming that all nodes are within range and in line-of-sight of each other. In such environments, and when in addition the propagation delay is small compared to the transmission time of a packet, analysis has clearly demonstrated the high channel utilization of CSMA and its superiority over the ALOHA schemes [9]. However analysis has also shown that CSMA suffers severe degradation when *hidden nodes* are present (i.e., when all nodes are not within range and in line-of-sight of each other) [20]. This situation is clearly met in multihop packet radio networks and hence in such networks CSMA is expected to perform rather poorly. The busy tone multiple access scheme (BTMA) attempts to overcome the hidden node problem by having a node transmit a busy tone when it is busy receiving, thus blocking its neighbors from interfering with its reception [13, 20]. This technique does not prevent all possible collisions since as with CSMA there is a vulnerable period in which collisions may occur. This is the time taken from the beginning of the packet transmission until the busy tone is detected by the neighbors of the destination. A pessimistic upper bound often assumed for this vulnerable period is twice the maximum propagation delay between pairs of neighboring nodes in the network. Several variants of BTMA exist depending on whcih set of nodes transmit the busy tone in any given situation as outlined below:

i. Conservative BTMA (C-BTMA): Whenever a node senses a transmission, it emits a busy tone regardless of whether it is the immediate destination or not. Then any node that wishes to transmit is allowed to do so only if it is not already transmitting, no transmissions from its neighbors are sensed and no busy tone is sensed. Note that if the propagation delay between nodes is zero, then C-BTMA is collision free.

ii. Idealistic BTMA (I-BTMA): This scheme is similar to C-BTMA except that whenever a node senses a transmission it emits a busy tone only if it is the immediate

destination. Without prior knowledge a node may not know if a particular transmission is destined do it or not, hence the name idealistic. It was considered for comparison purposes.

iii. Hybrid BTMA (H-BTMA): In I-BTMA we assume hypothetically that as soon as a node receives a packet it knows immediately whether or not that packet was destined for it. In practice this information is obtained from the packet header. Assuming that the packet header is processed as soon as it is received and before the entire packet is received, the time at which a node can determine whether or not it is the intended immediate destination for a particular packet reception is at the end of the processing of the packet header. In H-BTMA, a node operates as in C-BTMA until the header is processed, upon which time it operates as in I-BTMA. Alternatively one may conceive of a scheme in which the node operates as in CSMA until the header is processed prior to switching to I-BTMA. We considered only the former scheme in this study.

iv. Improved Idealistic BTMA (II-BTMA): Depending on the particular situation, both C-BTMA and I-BTMA have their shortcomings. In order to see how good a performance is achievable using random multiaccess protocols in multihop packet radio networks, we considered the following hypothetical II-BTMA protocol: As in I-BTMA, only the immediate destination emits a busy tone. Then, if a node wants to transmit, it is allowed to do so only if it is not already transmitting, it is not already receiving a packet destined to it, no busy tone is sensed, and its immediate receiver is not currently sensing carrier. The essence of II-BTMA is that given the state of the network in terms of ongoing transmissions, a scheduled transmission in the network is allowed to take place if it has a high probability of not interfering with an ongoing transmission; furthermore, once allowed, the transmission has a high probability of success. The implementation of this protocol may be difficult and expensive, given all the information needed to determine the right of transmission. However with enough resources, the implementation can be made feasible. For example one possibility is the use of a busy tone emitted by a

node when it is receiving a packet destined to it, and the use of a carrier sense tone emitted by a node when it is detecting carrier due to a packet transmission not destined to it; it is required that the carrier sense tone be coded so that it allows unique identification of the node emitting it.

An alternative solution to the problem of collisions in multiaccess/broadcast networks is based on spread spectrum and code division techniques. With these techniques the number of collisions may be reduced by using different orthogonal signalling codes in conjunction with matched filters at the intended receivers. Multiple orthogonal codes are obtained at the expense of increased bandwidth (in order to spread the waveforms). Code division techniques can be imbedded in random access schemes giving rise to schemes known as spread spectrum multiple access (SSMA) and code division multiple access (CDMA) [6a]. The following is an example of a CDMA scheme considered in our study.

v. CDMA-ALOHA: This protocol is implemented by means of the spread spectrum technique. Each node is assigned a unique code for reception. Nodes wishing to transmit to a particular node must use the code assigned to that node. A receiver that is idle 'locks onto' a packet with the appropriate code by correctly receiving a preamble appended in front of the transmitted packet. We assume that preambles are of infinitely short duration and that the presence of any number of overlapping transmissions on the channel does not affect the captured packet's reception. (Thus perfect capture is assumed.) When reception of a packet is completed the receiver becomes free until another packet with the correct preamble is received. With these conditions a node is allowed to transmit only if it is neither transmitting nor receiving.

Relatively little work has been done on the development of analytic models for multihop networks. Recently some significant advances have been made in [3, 4, 15, 16, 18, 22]. However, the models considered are restrictive as to the topological configurations considered, or the access schemes analyzed, or the performance measures

obtained. For example in [15] and [16] the topology was restricted to a two hop centralized configuration; in [3], [4], and [18] the model is restricted to exponential packet lengths, zero propagation delay and gives no information about packet delay; in [22] only the slotted ALOHA protocol is considered. The difficulty in dealing with the general problem analytically, and the limitations of the analytic models so far devised has motivated us to write a general purpose simulation program to investigate BTMA modes and to compare them to ALOHA, CSMA and CDMA modes.

The program is written in PASCAL and is modular and extendible. The topology, routing scheme, buffer capacity, packet parameters and traffic parameters are all inputs to the program. It is used to give insight into the behavior of the various protocols by comparing them under identical conditions for all other design variables. The program has additional value in that it can also be used to verify approximate analytic models and to test the effect of simplifying assumptions.

An example of a six node ring was considered to derive numerical results. For this example, it was shown that C-BTMA, which is relatively easy to implement, achieves significantly better performance than ALOHA and CSMA schemes. In particular, it achieves a factor of 2.5 increase in throughput over CSMA. The results presented did not take into account any bandwidth associated with the use of a busy tone channel. However it is exxpected that the significant improvement in bandwidth utilization achieved by BTMA in environments with hidden nodes, may well more than compensate for the cost of the busy tone channel.

Detailed discussion of all the results obtained can be found in *SEL Technical Report #234*, November 1982.

4. List of Publications and Technical Reports

A. Technical Reports

Tobagi, F. A. *Distribution of Packet Delay and Interdeparture Time in Carrier*

Sense Multiple Access. Stanford Electronics Laboratories Technical Report #187, Stanford: Stanford University, 1980.

Gonzalez-Cawley, Noel and Fouad A. Tobagi. *Simulation of Message-Based Priority Functions in Carrier Sense Multiaccess/Broadcast Systems*. Stanford Electronics Laboratories Technical Report #213, Stanford: Stanford University, 1981.

Tobagi, F. and David Shur. *Simulation of Busy Tone Multiple Access Modes in Multihop Packet Radio Networks*. Stanford Electronics Laboratories Technical Report #234, Stanford: Stanford University, 1982.

B. Journal Publications

Tobagi, F. A. "Carrier Sense Multiple Access With Message-Based Priority Functions," *IEEE Transactions on Communications, Vol. COM-30, No. 1,* January 1982.

Tobagi, F. A. "Distributions of Packet Delay and Interdeparture Time in Slotted ALOHA and Carrier Sense Multiple Access," *Journal of the Association for Computing Machinery, Vol. 29, No. 4,* October 1982, pp. 907–927.

C. Conference Papers

Tobagi, F. A. and N. Gonzalez-Cawley. *On CSMA-CD Local Networks and Voice Communication*. INFOCOM '82, Las Vegas, April 1982.

5. List of All Participating Scientific Personnel

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